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RESEARCH MEMORANDUM

WIND-TUNNEL INVESTIGATION OF NACA 65,3-418 AIRFOIL SECTION WITH BOUNDARY-LAYER CONTROL THROUGH A SINGLE SUCTION SLOT APPLIED TO A PLAIN FLAP

By

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SUMMARY

An investigation was conducted in the Langley two-dimensional low-turbulence tunnel of the NACA 65,3-418 airfoil section having a 25-percent-airfoil-chord plain flap and a suction slot on the flap. The tests were conducted at a Reynolds number of 3.20×10^6 for the aerodynamically smooth condition and with leading-edge roughness. The purpose of the investigation was to determine the effect of this type of boundary-layer control on the section lift-drag ratio.

The results of the investigation indicated that a flow coefficient of 0.0015 was sufficient to delay separation over the flap for a flap deflection of 20° up to a lift coefficient of 1.37 for the smooth model and for a flap deflection of 15° up to a lift coefficient of approximately 1.0 for the model with leading-edge roughness. For a flap deflection of 20° the total drag coefficient, including the drag coefficient equivalent of the boundary-layer control power, was 0.0048 at a lift coefficient of 1.37 for the smooth model; the corresponding value of the section lift to total-drag ratio was 286. Boundary-layer control was ineffective, however, in producing any substantial decrease in the minimum section drag coefficient of the smooth model. Boundary-layer control for the model with leading-edge roughness produced a substantial decrease in the section drag coefficient at low as well as at high lift coefficients. For the model with leading-edge roughness and a flap deflection of 15°, the total drag coefficient was 0.0097 at a lift coefficient of 1.0; the corresponding value of the section lift to total-drag ratio was 103. The data indicate that the maximum lift to total-drag ratio of finite-span wings of reasonable aspect ratio made up entirely of NACA 65,3-418 airfoil sections would not be improved by this type of boundary-layer control for the aerodynamically smooth condition; however, the maximum lift to total-drag ratio for the rough leading-edge condition would be increased by this type of boundary-layer control but would still be less than that of the aerodynamically smooth wing.

INTRODUCTION

As reported in references 1 and 2, high values of the section lift-drag ratio were obtained by the use of a highly cambered NACA 65,3-618 airfoil section. The airfoil section was equipped with a 0.20-chord plain flap to permit a variation in the effective camber and thereby increase the range of lift coefficients for low drag. The maximum value of the section lift-drag ratio obtained in references 1 and 2 was 178, and this value was obtained with a downward flap deflection of 5°. It seemed likely that substantially higher values of the section lift-drag ratio would be obtained if it were possible to delay separation of the turbulent boundary layer over the flap and thereby avoid the excessive increments of drag usually associated with the larger flap deflections.

Boundary-layer control by suction or blowing is a well-known method of delaying separation. Suction is, however, generally more economical of power than blowing. The purpose of the present investigation is to determine the increase in section lift-drag ratio obtainable with boundary-layer control by suction applied to a plain flap. The tests were made in 1942 in the Langley two-dimensional low-turbulence tunnel on an NACA 65,3-418 airfoil section equipped with a 0.25-chord plain flap.

COEFFICIENTS AND SYMBOLS

c_l	section lift coefficient $\left(l/q_o c\right)$
c_d	section wake drag coefficient, determined from measurements in the wake $\left(d/q_o c\right)$
c_{d_b}	blower drag coefficient $\left(C_Q C_P\right)$
c_{d_T}	section total drag coefficient $\left(c_d + \frac{\eta_p}{\eta_b} c_{d_b}\right)$
C_Q	flow coefficient $\left(Q/V_o cb\right)$
C_P	pressure-loss coefficient $\left(\frac{H_o - H_b}{q_o}\right)$
l	lift per unit span, pounds per foot
d	drag per unit span, pounds per foot
c	chord of airfoil with flap neutral, feet

b span over which boundary-layer control is applied, feet

S wing area, square feet

Q volume rate of flow through suction slot, cubic feet per second

H_o free-stream total pressure, pounds per square foot

H_b total pressure in wing duct, pounds per square foot

V_o free-stream velocity, feet per second

q_o free-stream dynamic pressure, pounds per square foot

ρ_o free-stream mass density, slugs per cubic foot

α_o angle of attack for infinite aspect ratio or section angle of attack, degrees

δ_f flap deflection, positive downward, degrees

R Reynolds number

η_b combined duct and blower efficiency

η_p efficiency of main propulsive unit

L lift of wing, pounds

D drag of wing, pounds

P_b power input to blower, foot-pounds per second

P_p power input to propulsive unit, foot-pounds per second

MODEL

The 3-foot-chord NACA 65,3-418 model used in this investigation was constructed of laminated mahogany and completely spanned the 3-foot-wide test section of the Langley two-dimensional low-turbulence tunnel.

Ordinates of the NACA 65,3-418 airfoil section are given in table I. The 25-percent-chord plain flap was pivoted on leaf hinges mounted flush with the lower surface of the airfoil section. The ordinates of the flap are the same as the ordinates given in table I for the trailing-edge part of the NACA 65,3-418 airfoil section. The suction slot 0.0035c in width was located just to the rear of the intersection of the flap hinge radius and the flap upper surface or in terms of the airfoil chord at approximately 0.80c. A sketch of the model is presented in figure 1. The suction slot as shown in figure 1 was inclined forward with the forward lip well rounded and the rear lip sharp.

TESTS

Tests of the NACA 65,3-418 airfoil section were made in the Langley two-dimensional low-turbulence tunnel at the optimum flow coefficient for minimum drag and for maximum lift-drag ratio. The optimum flow coefficient was determined by a series of preliminary tests at low section angles of attack with various flow coefficients. The tests were conducted at a Reynolds number of 3.2×10^6 for the model smooth and with standard leading-edge roughness. (See reference 2.)

Lift and drag of the model for various flap deflections were measured by means of tunnel floor and ceiling pressure orifices and wake survey apparatus, respectively. A detailed discussion of the test equipment and its use in the Langley two-dimensional low-turbulence tunnels and the methods used in correcting the test data to free-air conditions are given in reference 2.

Quantity of flow through the suction slot was measured by means of a venturi meter. Loss of total pressure through the slot was obtained from the difference between free-stream total pressure and the total pressure within the duct as measured by a flush-type orifice located in the end of the duct opposite to the end from which the air was removed. For the rates of flow involved in this investigation the velocities in the duct of the model were sufficiently low that the pressure as measured by the flush orifice within the duct could be assumed to be total pressure.

RESULTS AND DISCUSSION

The test results of the investigation are presented in figures 2 and 3. The section wake-drag and total drag coefficients are given as functions of the lift coefficient for similar conditions of flow and flap deflection in figures 2 and 3, respectively. The data are presented for a Reynolds number of 3.2×10^6 for the model aerodynamically smooth and with standard leading-edge roughness. For the no-flow condition the suction slot was sealed and faired to the airfoil contour.

As expected, the removal of a portion of the boundary layer by means of a suction slot on the flap results in a decrease in the measured wake drag (fig. 2). The drag-coefficient equivalent of the power required for the boundary-layer control should, however, be added to the wake-drag coefficient to obtain the equivalent total drag coefficient of the section. The suction power may be expressed as

$$P_b = \frac{C_Q C_P}{\eta_b}\frac{1}{2}\rho_o V_o{}^3 S = \frac{\frac{1}{2}\rho_o V_o{}^3 S}{\eta_b} c_{d_b}$$

and the power expended by the main propulsive unit in overcoming the wake drag is

$$P_p = \frac{1}{2}\frac{\rho_o V_o{}^3 S}{\eta_p} c_d$$

Then the total equivalent drag coefficient may be defined as

$$c_{d_T} = \frac{P_p + P_b}{\frac{1}{2}\rho_o V_o{}^3 S}\eta_p = c_d + \frac{\eta_p}{\eta_b} c_{d_b}$$

Values of the total drag coefficient presented in this paper based on the assumption that $\frac{\eta_p}{\eta_b} = 1$. This relation may be expected to be satisfied approximately for propeller-driven airplanes. For jet-driven airplanes, however, η_p may be expected to be considerably less than η_b.

Figure 3 shows that the addition of boundary-layer control was ineffective in reducing the total drag coefficient of the smooth model over the normal range of lift coefficient for low drag; that is, from $c_l = 0$ to $c_l = 0.6$. For lift coefficients above 0.6, however, the combination of flap deflection and boundary-layer control produced large decreases in the drag coefficients. With roughness applied to the leading edge, the NACA 65,3-418 airfoil section is subject to incipient separation of the flow near the trailing edge even with the flap neutral and therefore boundary-layer control was effective in producing a substantial reduction in the total drag coefficient over the entire range of lift coefficient investigated. In no case, however, was the total drag coefficient with leading-edge roughness as low as that for the smooth airfoil.

The data of figure 3 indicate that boundary-layer control was effective in delaying separation over the flap up to a flap deflection of 20° and a lift coefficient of 1.37 for the model smooth and up to a flap deflection of at least 15° and a lift coefficient of 1.0 for the configuration with leading-edge roughness.

The minimum total drag coefficients obtained with the plain flap deflected were approximately the same as those for flap neutral but occurred at much higher lift coefficients. The section lift to total-drag ratios obtained with boundary-layer control on the deflected flap were, consequently, much higher than those for the basic section without boundary-layer control. This effect is shown more clearly in figure 4 where the section lift to total-drag ratio has been plotted against section lift coefficient. The maximum section lift to total-drag ratio was increased from 118 to 286 for the model in the smooth condition and from 39 to 103 for the model with leading-edge roughness. The value of the lift to total-drag ratio of 286 obtained with the smooth model, where the boundary-layer flow was laminar up to approximately 50 percent of the chord, is considerably higher than the value of 178 given in references 1 and 2 for the NACA 65,3-618 airfoil section with a plain flap without boundary-layer control, and is somewhat higher than the value of 250 obtained by Pfenninger in some unpublished test results for a 17-percent-thick airfoil section having a 10.6-percent-chord flap and boundary-layer control. The method of applying boundary-layer control is presumably similar to some of those described in reference 3.

There is some doubt, however, regarding the practical utility at cruising conditions of the high values of section lift to total-drag ratio obtained for the smooth section in the present investigations because of the relatively high value of the lift coefficient at which the maximum section lift to total-drag ratio occurs. If the section profile drag does not vary with lift coefficient, the maximum lift-drag ratio of a finite-span wing occurs when the induced drag is equal to the profile drag. For wings of moderate aspect ratio made up of relatively low-drag wing sections the lift coefficient for maximum lift-drag ratio is relatively low. For example, the maximum value of the lift-drag ratio of an elliptical wing composed of NACA 65,3-418 airfoil sections and having an aspect ratio of 10 is 40, but this maximum value occurs for a wing lift coefficient of 0.39. The fact that the section drag coefficient remains substantially constant up to a lift coefficient of 1.3, therefore, has no effect on the maximum value of the wing lift-drag ratio except possibly for wings of impractically high aspect ratios. On the other hand, the use of boundary-layer control on the flap of the section with leading-edge roughness would result in some improvement of the characteristics of a finite-span wing of reasonable aspect ratio because in this case boundary-layer control was effective in reducing the section profile-drag coefficient at low as well as at high lift coefficients.

CONCLUSIONS

Tests of the effectiveness of boundary-layer control by a single suction slot located on the upper surface immediately downstream of the hinge location of a 0.25-chord plain flap on an NACA 65,3-418 airfoil section indicate the following conclusions:

1. A flow coefficient of 0.0015 was sufficient to delay separation over the flap for a flap deflection of 20° up to a lift coefficient of 1.37 for the smooth model and for a flap deflection of 15° up to a lift coefficient of approximately 1.0 for the model with leading-edge roughness.

2. For the 20° flap deflection, the total drag coefficient, including the drag coefficient equivalent of the boundary-layer control power, was 0.0048 at a lift coefficient of 1.37 for the smooth model; the corresponding value of the section lift to total-drag ratio was 286.

3. Boundary-layer control was ineffective in producing any substantial decrease in the minimum section drag coefficient of the smooth model.

4. Boundary-layer control for the model with leading-edge roughness produced a substantial decrease in the section drag coefficient at low as well as at high lift coefficients.

5. For the model with leading-edge roughness and a flap deflection of 15°, the total drag coefficient was 0.0097 at a lift coefficient of 1.0; the corresponding value of the section lift to total-drag ratio was 103.

6. The data indicate that the maximum lift to total-drag ratio of finite-span wings of reasonable aspect ratio made up entirely of NACA 65,3-418 airfoil sections would not be improved by this type of boundary-layer control for the aerodynamically smooth condition; however, the maximum lift to total-drag ratio for the rough leading-edge condition would be increased by this type of boundary-layer control but would still be less than that of the aerodynamically smooth wing.

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REFERENCES

1. Abbott, Ira H., and Miller, Ralph B.: Tests of a Highly Cambered Low-Drag-Airfoil Section with a Lift-Control Flap. NACA ACR, Dec. 1942.

   Abbott, Ira H., and Miller, Ralph B.: Supplement to Advance Confidential Report, Tests of a Highly Cambered Low-Drag-Airfoil Section with a Lift-Control Flap. NACA ACR No. 3D30, 1943.

2. Abbott, Ira H., Von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA Rep. No. 824, 1945.

3. Pfenninger, Werner: Investigations on Reductions of Friction on Wings, in Particular by Means of Boundary-Layer Suction. NACA TM No. 1181, 1947.

TABLE I

NACA 65,3-418 AIRFOIL SECTION

[Stations and ordinates in percent airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.280	1.406	.720	-1.206
.504	1.720	.996	-1.440
.974	2.199	1.526	-1.771
2.184	3.082	2.816	-2.338
4.643	4.446	5.357	-3.182
7.125	5.534	7.875	-3.838
9.622	6.445	10.378	-4.377
14.638	7.904	15.362	-5.212
19.672	9.019	20.328	-5.835
24.717	9.878	25.283	-6.298
29.769	10.509	30.231	-6.621
34.825	10.926	35.175	-6.806
39.884	11.131	40.116	-6.847
44.943	11.106	45.057	-6.726
50.000	10.799	50.000	-6.387
55.051	10.235	54.949	-5.855
60.094	9.458	59.906	-5.174
65.127	8.509	64.873	-4.389
70.148	7.428	69.852	-3.540
75.156	6.243	74.844	-2.663
80.149	4.979	79.851	-1.795
85.128	3.667	84.872	-.975
90.092	2.355	89.908	-.287
95.046	1.122	94.954	.142
100.000	0	100.000	0

L.E. radius: 1.920
Slope of radius through L.E.: 0.168

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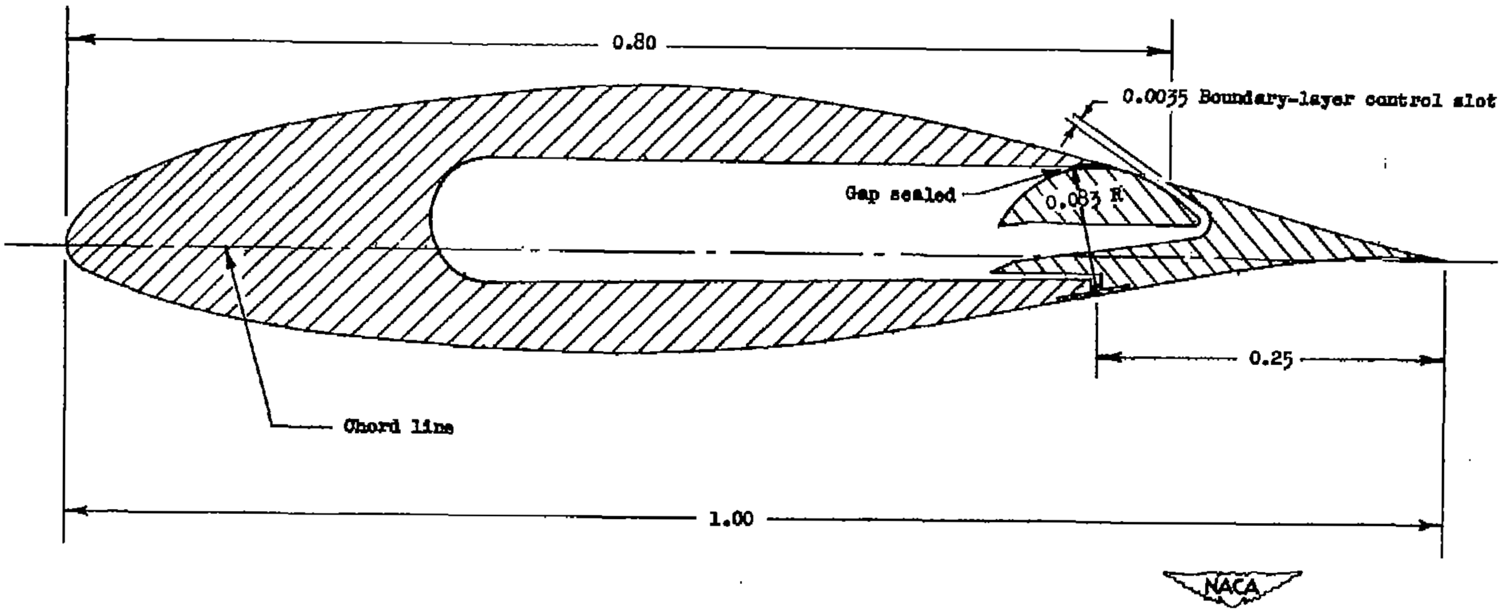


Figure 1.- Profile of the NACA 65,3-418 airfoil section with a 25-percent-airfoil-chord plain flap showing the boundary-layer control slot and its location.

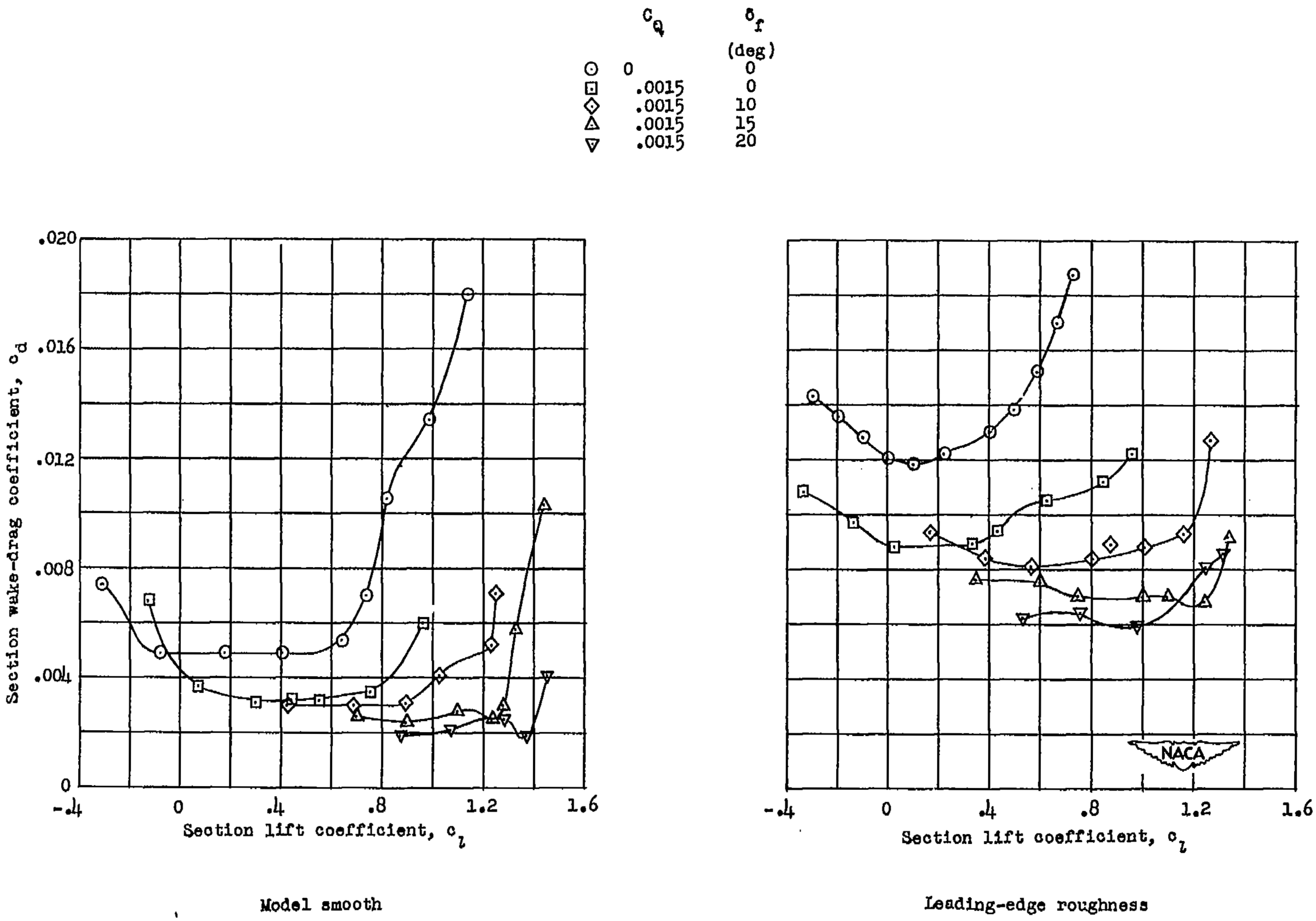
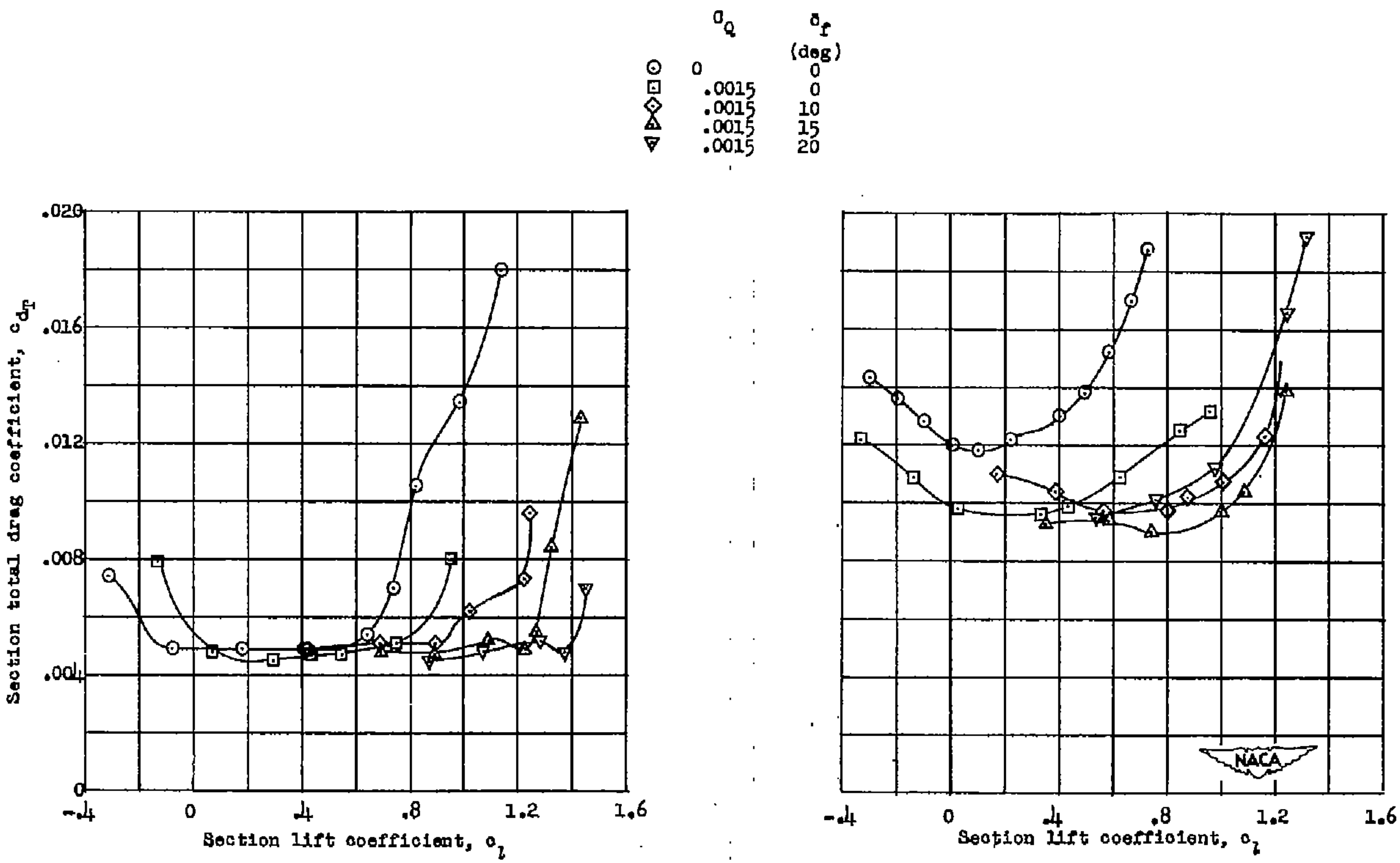


Figure 2.- Section wake-drag characteristics of the NACA 65,3-418 airfoil section with a 0.25c plain flap and a boundary-layer control slot at 0.80c. $R = 3.2 \times 10^6$.



Model smooth

Leading-edge roughness

Figure 3.- Section total-drag characteristics of the NACA 65,3-418 airfoil section with a 0.25c plain flap and a boundary-layer control slot at 0.80c. $R = 3.2 \times 10^6$.

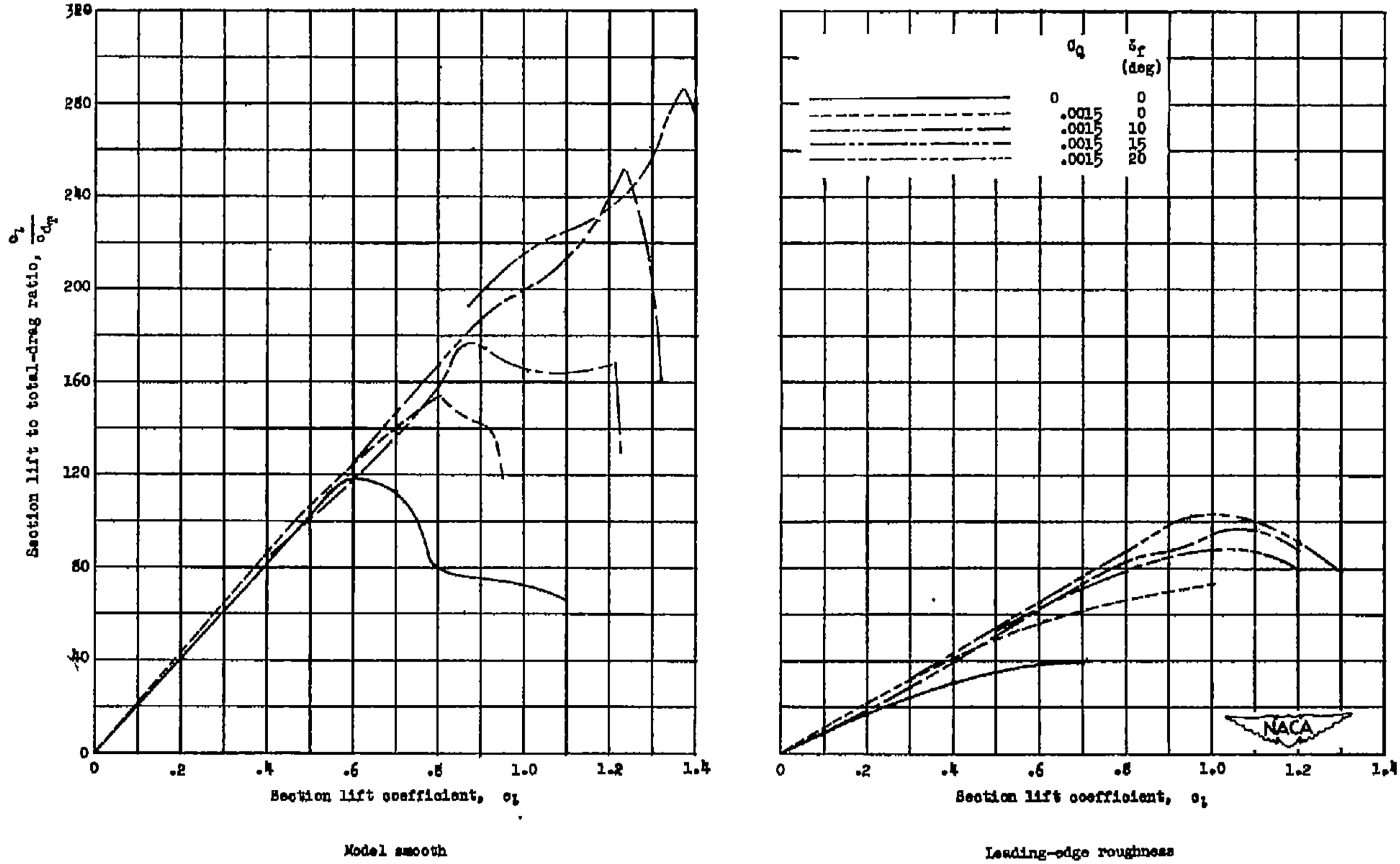


Figure 4.- Section lift to total-drag ratio characteristics of the NACA 65,3-418 airfoil section with a 0.25c plain flap and a boundary-layer control slot at 0.80c. $R = 3.2 \times 10^6$.